Flavor Bounds and Phenomenology in the Scalar Sector of RS Scenarios[*]

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(Dated: May 19, 2010)

Abstract

In the context of a warped extra-dimension with Standard Model fields in the bulk, we obtain the general flavor structure of the couplings to fermions of both the Higgs scalar and the radion graviscalar. In the Flavor Anarchy paradigm, these couplings are generically misaligned with respect to the fermion mass matrix and moreover the off-diagonal couplings can be estimated parametrically as a function of fermion masses and the observed mixing angles. One can then study the flavor constraints and predictions arising from these couplings.

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[*] Talk presented at SUSY09 Conference, Northeastern University, Boston, MA

Scenarios with a warped extra-dimension were introduced to address the hierarchy problem [1] but one can simultaneously attack the flavor hierarchy puzzle of the Standard Model by placing all the fields (except the Higgs) in the Bulk. The observed hierarchies in masses and mixings in the fermion sector are explained by small overlap integrals between fermion wave functions and the Higgs wave function along the extra dimension. The electroweak precision tests push the possible scale of new physics at around a few TeV [2] and $\Delta F = 2$ processes push the generic bound to be above ~ 10 TeV [3] (see also for example [4, 5]), making it very hard to produce and observe heavy resonances of this mass at the LHC (see also [6] for possible ways of softening this bound and [7] for possible limitations).

Generically, these models contain in their spectrum two light scalars, namely the Higgs and the radion. The Higgs scalar can arise as a single 4D scalar localized on the TeV boundary, or as the lightest Kaluza-Klein mode of a 5D bulk Higgs. The radion graviscalar can be thought of as a scalar component of the 5D gravitational perturbations, and basically it tracks fluctuations of size of the extra-dimension (i.e. its "radius"). It has recently been pointed out that in this context, one generically expects some amount of flavor changing neutral currents (FCNC's) mediated by both the Higgs [8, 9] and the radion [10]. The 5D spacetime we consider takes the usual Randall-Sundrum form [1]:

$$ds^2 = \frac{1}{(kz)^2}\Big(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2\Big), \tag{1}$$

where k is the curvature scale of the AdS space. Let's focus on the down-quark sector of a simple setup in which we consider the 5D fermions Q, D (containing the 4D SM $SU(2)_L$ doublet and singlet), with 5D action

$$S_d = \int d^4x dz \sqrt{g} \Big[\frac{i}{2}\, \bar{Q}\slashed{D}\, Q + \frac{c_q}{R}\bar{Q}Q + (Q \to D) + \big(Y_d\, \bar{Q}HD + h.c.\big)\Big], \tag{2}$$

where c_q and c_d are the 5D fermion mass coefficients. Since the Higgs H is localized towards the TeV boundary, it is useful to work with the value of the fermion zero-modes wavefunctions at that boundary, i.e $f_c \equiv \sqrt{\frac{1-2c}{1-\varepsilon^{1-2c}}}$, where $\varepsilon \approx 10^{-15}$ is the warp factor. When $c > 1/2$ the dependence on the fermion bulk mass parameter c is exponentially sensitive, leading to the explanation of mass hierarchies in this scenario.

It turns out that generically one should expect some misalignment between the SM fermion mass matrix and the Higgs Yukawa coupling matrix [8], irrespective of the Higgs being exactly brane localized or leaking into the bulk [9]:
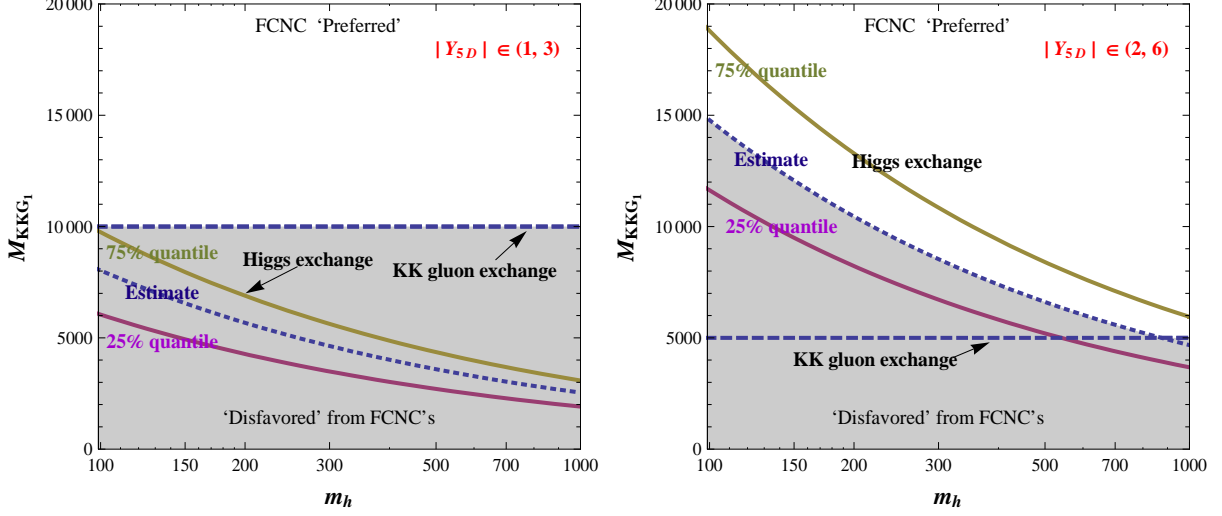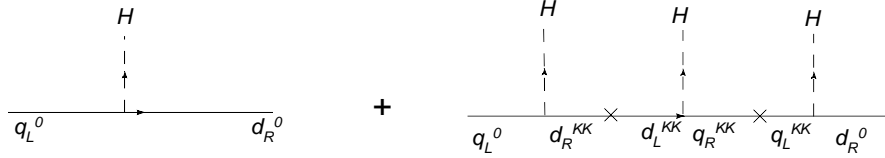
FIG. 1: Generic bounds from ϵ_K in the plane ($m_h - M_{KKG1}$) due to Higgs exchange and KK gluon exchange, for two ranges of the 5D Yukawas Y (left and right).

From the second diagram, we see that when the Higgs acquires its vev, only one term will contribute to the fermion mass, whereas three terms (from three different combinations) will contribute to the Yukawa coupling between the physical Higgs and two fermions, therefore potentially misaligning both matrices in flavor space. If we parametrize the Yukawa couplings of the Higgs as $\mathcal{L}_{HFV} = a_{ij}^d \sqrt{\frac{m_i^d m_j^d}{v_4^2}} H \bar{d}_L^i d_R^j + h.c.$ we can then estimate the size of these as

$$a_{ij}^d \sim \delta_{ij} - \frac{2}{3} \frac{Y^2 v_4^2}{M_{KK}^2} \begin{pmatrix} 1 & \lambda \sqrt{\frac{m_s}{m_d}} & \lambda^3 \sqrt{\frac{m_b}{m_d}} \\ \frac{1}{\lambda} \sqrt{\frac{m_d}{m_s}} & 1 & \lambda^2 \sqrt{\frac{m_b}{m_s}} \\ \frac{1}{\lambda^3} \sqrt{\frac{m_d}{m_b}} & \frac{1}{\lambda^2} \sqrt{\frac{m_s}{m_b}} & 1 \end{pmatrix} \tag{3}$$

where $\lambda \sim 0.22$ is the Cabibbo angle. The couplings for the up quark sector can be found by simply replacing the down quark masses by the up quark masses. With these estimates, we then perform a random scan on the flavor parameters of the setup leading to correct masses and mixings, and obtain a distribution of the normalized Yukawa couplings $a_{ij}^{d,u}$. In Figure 1 we show the bounds coming from ϵ_K in $\bar{K} - K$ mixing, in the plane m_h-M_{KKG}, where
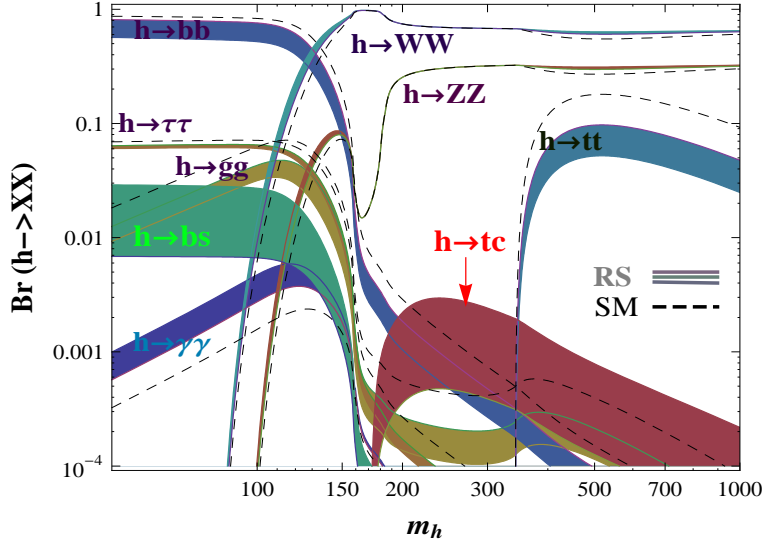
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FIG. 2: Branching ratios of the Higgs in the SM and in RS, with possible new flavor violating decays such as $h \to tc$ or $h \to bs$, for a KK scale of $M_{KKG1} = 3.7$ TeV and $Y_i \sim (1\text{-}4)$.

M_{KKG} is the first KK gluon mass. On the left panel we consider smaller 5D Yukawa values, and include a 10 TeV bound due to KK gluon exchange. On the right panel, we consider 5D Yukawas twice as large, and show how this tightens the Higgs exchange bounds and reduces KK gluon exchange tensions (although these large Yukawas put the setup on the limits of 5D perturbativity).

In Figure 2 we show how the Branchings of the Higgs change because of the new flavor violating couplings. There is a generic suppression in the diagonal couplings (specially to tops and bottoms) which results in lower Branchings to fermions. Interestingly this results in an enhanced Branching into photons, although the overall Higgs production at the LHC will be also be generically suppressed in the gluon fusion channel. Nevertheless one expects that some of these features will be observed at the LHC. Then one could probe for exotic decays such as $h \to tc$, if kinematically allowed (this will be true for the radion too).

The radion graviscalar can be parametrized as a scalar perturbation of the metric:

$$ds^2 = \left(\frac{R}{z}\right)^2 (e^{-2F}\eta_{\mu\nu}dx^\mu dx^\nu - (1+2F)^2 dz^2) \qquad (4)$$

Demanding that the perturbed metric solves the Einstein equation and that the Radion field is canonically normalized, we get $F = \frac{r(x)}{\Lambda_r}\frac{z^2}{R'^2}$ where $r(x)$ is the corresponding canonically normalized radion graviscalar with its associated interaction scale $\Lambda_r = \sqrt{6}\ \varepsilon\ M_{Pl}$, where
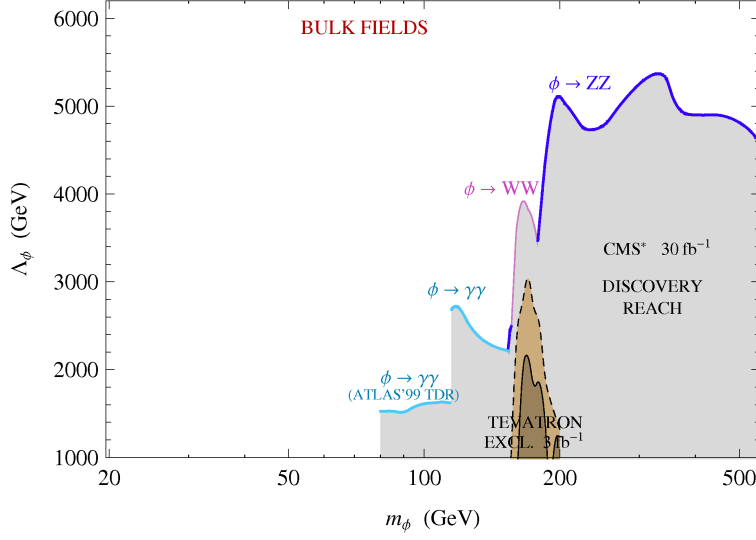
FIG. 3: LHC discovery reach for the radion using "translated" Higgs projections from CMS (and ATLAS in the lower mass region) for $30 fb^{-1}$ of luminosity.

again $\varepsilon \sim 10^{-15}$. This scale is of TeV size and therefore the radion can have interesting collider phenomenology [11, 12]. In Figure 3, the LHC discovery reach for the radion is plotted as a function of its mass and the interaction scale Λ_r.

Similarly to the Higgs, its couplings to fermions can be parametrized as $\mathcal{L}_{rFV} = \frac{1}{\Lambda_r}\tilde{a}^d_{ij}\sqrt{m^d_i m^d_j} \ r(x)\bar{d}^i_L d^j_R \ + h.c.$ and these can have off-diagonal entries, which we estimate as [10]:

$$
\tilde{a}^d_{ij} \sim \begin{pmatrix} (c_{q_1} - c_{d_1}) & (c_{q_1} - c_{q_2})\lambda\sqrt{\frac{m_s}{m_d}} & G(c_{q_i})\lambda^3\sqrt{\frac{m_b}{m_d}} \\ (c_{d_1} - c_{d_2})\frac{1}{\lambda}\sqrt{\frac{m_d}{m_s}} & (c_{q_2} - c_{d_2}) & (c_{q_2} - \frac{1}{2})\lambda^2\sqrt{\frac{m_b}{m_s}} \\ F(c_{d_i})\frac{1}{\lambda^3}\sqrt{\frac{m_d}{m_b}} & (c_{d_2} - c_{d_3})\frac{1}{\lambda^2}\sqrt{\frac{m_s}{m_b}} & (\frac{1}{2} - c_{d_3}) \end{pmatrix} \tag{5}
$$

where F and G are some combination of c_i's and extending to the up quark sector is immediate. Generic bounds can again be obtained, in particular those coming from ϵ_K in $\bar{K} - K$ mixing, as shown in Figure 4, where it is seen that a very light radion is highly disfavored. After discovering the radion at the LHC (say from $r \to ZZ$ decays), it would be important to search for exotic decays such as $r \to tc$.

We conclude with the message that the two potentially light scalars of these scenarios, which presumably could be discovered at the LHC have some amount of Flavor Violating couplings, and probing these will be a very important probe on the origin of flavor and of
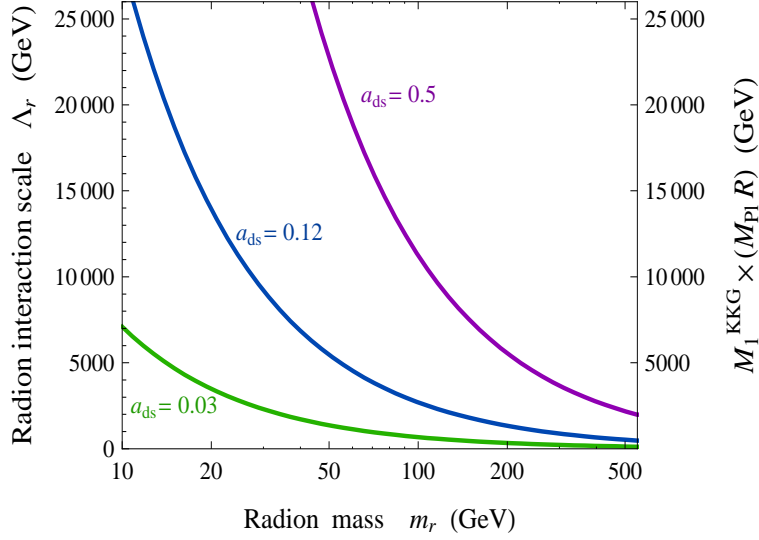
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FIG. 4: Generic bounds from ϵ_K in the plane $(m_r - M_{KKG1})$ due to tree-level radion exchange.

these setups in general.

Acknowledgments

I would like to thank my collaborators Aleksandr Azatov and Lijun Zhu as well as Kaustubh Agashe for discussions and comments.

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